8. UNCERTAINTY MITIGATION: MANAGING UNCERTAINTY WITH CONTINGENCIES AND TOLERANT DESIGNS

Introduction

The second means for managing uncertainty is mitigation through use of robust designs and contingency plans. All uncertainties that cannot be or are not reduced to a level of insignificance must be mitigated. Whereas reduction efforts are focused on decreasing the range of probable values for an unknown parameter or condition in hopes of rendering it too narrow to span the decision threshold; mitigation is directed towards moving the threshold to a point outside of the range of possible values for the unknown parameter or condition (as shown in Figure 5-2).

This chapter discusses the options available for uncertainty mitigation. It describes the nature of residual uncertainties commonly found at sites and the degree to which they lend themselves to tolerant (robust) technologies or contingency plans to counteract the effects of deviations from conditions assumed, in order to proceed with remedial action design and implementation. Variations of the uncertainty matrix are provided to illustrate its use in both pre-decision document and post-decision document phases of work. In order to design responses and select effective contingencies, the PMT must be able to reach consensus on the intent of the decision document and the breadth of flexibility it allows. The factors relevant to determining the degree to which contingencies must be developed are also discussed.

Nature of Residual Uncertainties

Ultimately, the PMT will arrive at the point where a decision must be made with no further data collection to support that decision. There are many uncertainties that can arise that defy uncertainty reduction or are so difficult to reduce that they are best managed through mitigation with contingencies. An example of the latter uncertainties arises when there is a need to prove the negative (i.e., prove that a given condition or problem does not exist anywhere on an installation). In other cases, the geologic complexity is such that the tools are not available to definitively characterize all regions of interest (e.g., karst or fractured rock systems). The PMT must recognize and deal with those uncertainties early in the process.

Common examples of uncertainties that may remain regardless of site characterization approaches include:

- Existence and location of DNAPLs;

- Nature and interconnectivity of fracture flow or faulting;

- Presence of drums or "hot spots" in landfills;

- Presence of discrete waste container, object or agent alluded to in anecdotal records;

- Effectiveness of proposed response;

- Time required for response to meet remedial action objectives; and

- Probable future land uses over time.

Remaining uncertainties can arise because of the inability to reduce them through data collection, or a conscious decision by the PMT not to collect data, because it is more cost-effective to mitigate the uncertainty. Of those uncertainties remaining after site characterization, some may be reducible as a result of information gathered during implementation of the response or performance monitoring of the remedy (e.g., volume of contaminated soil to be excavated), and some may never be resolved (e.g., presence of a hot spot in a landfill that is to be capped). In either case, the PMT must plan for, and counteract, any adverse effects that could arise from conditions or values for those uncertainties different than the assumed values (most likely values) on which the decisions were based. This is accomplished through use of contingencies or technologies that are sufficiently robust as to have higher or no thresholds (situations in which they do not meet performance expectations) of significance.

On rare occasions, significant uncertainties impact the ability to completely define an unacceptable risk. More frequently, however, remaining uncertainties will impact selection and design of a response. In either case, these are uncertainties for which contingency planning or use of new investigation techniques is warranted.

The management strategy for uncertainty in problem definition (i.e., determine if risk is unacceptable) focuses on the tradeoffs between:

- Ongoing investigation (traditional techniques);

- Use of new investigation techniques;

- Implementation of a remedy as a safeguard against potential exposures; and

- Long-term monitoring as a compromise data collection effort.

For residual uncertainties associated with remedy selection and design, the PMT may select a conservative remedy that assumes worse case conditions, or identify monitoring and contingency plans capable of identifying deviations from assumed conditions soon enough to implement the required contingency.

Alternatives for Uncertainty Mitigation

Uncertainty mitigation focuses on changing the decision criteria for which the unknown data are required. Changes may result from using an alternate assumed value or condition that results in a more robust response for which the residual uncertainty is insignificant, or from identifying a contingency that can be implemented to counteract the impact of deviations from the assumed value. The nature of the preferred approach is a function of the type of residual uncertainty, the capability of available technologies, and the degree to which data bound the range of reasonable deviations from the assumed parameter value.

Consider the case of an uncertain exposure or risk. An area is known to have been used for escort training. Glass ampoules of chemical agent may have been buried after the exercises were complete. There is no cost-effective method to quickly determine the existence or location of these ampoules. If the site is assumed clean and released for unrestricted use, there is a potential for damages if ampoules are subsequently encountered. One means of mitigating this uncertainty is to assume the ampoules do exist, recognize the technical impracticability of clean closure, and opt for institutional controls through restricted access and retained ownership. In this case, the decision criterion has been eliminated because the course of action is protective regardless of whether or not the ampoules exist. In essence, the uncertainty has been rendered insignificant.

An example of uncertainty over the performance of a response would be the long-term stability of geochemical conditions required to support attenuation mechanisms central to a monitored natural attenuation remedy. In this case, no one can accurately predict if there will be future changes in background chemistry that could impact attenuation. Hence, the PMT may decide to monitor the geochemistry until attenuation has brought conditions to a state that meets the remedial action objectives (RAOs). Decision criteria are set to indicate when geochemical changes are sufficient to trigger implementation of an active remedy as a contingency that counteracts the loss of attenuation at the levels required to meet the RAOs. In this case, the decision criterion has been augmented by a second criterion (the decision threshold for the contingency action) that becomes operable if monitoring data signal the need.

Another example would be the case where the saturated zone is thought to contain conduits that are preferential pathways for plume migration. If a reasonable level of field investigation has failed to locate such conduits, the preferred remedy can be implemented utilizing sentinel wells in front of the potential receptor wells. This should be accompanied by a plan for well-head treatment or supplemental capture wells should contaminants reach the sentinel points at levels above response objectives. In this example, the presence of the conduits would be identified only if they threaten the receptor wells. Other conduits could exist, but if they do not threaten the receptor wells, the PMT can accept the uncertainty of their existence since their presence poses no risk and, therefore, constitutes an insignificant uncertainty.

Selecting Between Mitigation Alternatives

In selecting the likely response technology for environmental restoration, it is necessary to apply and integrate the Principles. Just as the overall activity begins with development of a problem statement, response selection begins with development of the performance objective. Typically, PMTs begin with the need to protect human health and the environment and then translate that into much greater detail, as it is refined to a site-specific application.

Similar to use of the CSM to bound and target site characterization activities, technology selection is bounded and focused by a subset of the CSM that quantitatively defines those parameters and conditions that will impact applicability and performance of the selected response. For those parameters or conditions that are uncertain, the PMT must assume a most probable value or state, based on the best available information. The uncertainties are characterized with respect to whether or not they are best resolved during implementation.

When the uncertainty is likely to be resolved during implementation, having a monitoring plan to alert the PMT that a deviation is likely, and contingency plans in place for any activation necessary can minimize impacts. This strategy is known as the Observational Approach. For example, an area of contaminated soil is thought to contain only trivalent chromium and is being exhumed and treated to immobilize the chromium with a solidification process that will not be effective on hexavalent chromium. The contingency plan for discovery of hexavalent chromium could be preprocessing with reducing agents to convert all chromium to the trivalent form prior to solidification. In this case, some means of chromium speciation would be used to monitor the soil as it is exhumed and detect the presence of hexavalent chromium.

When the uncertainty is not likely to be resolved during implementation, the contingency needs to be built into the response (i.e., the response technology needs to be tolerant of all the possible values or states for the uncertainty such that there are no adverse impacts regardless of what the true value is). This can be viewed as a special case of the Observational Approach, wherein the contingency is pre-mobilized. Alternately, this approach can be viewed as one based on assumptions of the most restrictive conditions for the design basis.

There is less flexibility inherent in this approach and a greater commitment of resources.

An example of a tolerant technology approach would be a treatment train for groundwater that may have iron precipitation problems that would affect air stripping. An iron removal process could be added to the train or air stripping could be replaced with activated carbon, a process that is less likely to suffer iron impacts.

Contingency plans and/or tolerant technologies are selected and developed to the degree required to ensure meeting performance objectives in a timely manner. The key is to identify and evaluate each uncertainty and then select the appropriate management strategy rather than not think through the potential consequences and have the decision made by default.

Alternative Uncertainty Matrices

Variations of the uncertainty matrix are a useful way to systematically address uncertainties. The preferred format is a modification of the matrix provided previously in Figure 5-4 to determine the significance of uncertainties. In one form (Figure 8-1), technologies are compared to determine their relative sensitivities to uncertainties. In a second (Figure 8-2), the selected technology is evaluated to select contingencies.

Figure 8-1: Uncertainty Matrix – Response Selection

Uncertainty	Assumed Value	Response	Threshold	Probability of Exceedance	Impact
Permeability 10^{-5} to 10^{-2} cm/s	10^{-3}	Pump and treat	$\leq 10^{-4}$	Low	Incomplete capture, excessive drawdown
		Permeable treatment wall	$\geq 10^{-3}$	Moderate	Insufficient contact time
		In situ bioremediation	$\leq 10^{-3}$	Moderate	Incomplete treatment due to poor mixing of nutrients
Preferential Conduits – Present or Absent	Absent	Pump and treat	Present	Moderate	Insufficient containment, risk to receptor wells
		Permeable treatment wall	None if have aquiclude to key in to	Low	
		In situ bioremediation	Present	Moderate	Incomplete treatment

Figure 8-2: Uncertainty Matrix– Response Design

Response	Parameter	Design Basis	Range of Values	Impact	Threshold for Impact (Probability)	Monitoring	Contingency	Time to Implement
Monitored Natural Attenuation	Long-term geochemical stability	Stable	Stable/ Unstable	Arsenic becomes mobile	ph > 8 ph < -3 (low)	Eh-ph, As in sentinel wells	Pump and treat	6 months
	Irreversibility of adsorption	Irreversible	Reversible/ Irreversible	Release of arsenic in future	>10% release (low)	As in sentinel wells	Pump and treat	6 months
	Presence of preferential pathways	None	Several	Arsenic escapes may be transported to well	>10% of flow (moderate)	Monitor receptor wells for As	Well had treatment	3 months
	Current perimeter is static	Static	Retreating to growing	No immediate effect due to buffer zone	Flux exceeds buffer zone > ¼ mile growth (moderate)	As in sentinel wells	Pump and treat	6 months
	Permanence of institutional controls	Non-residential	Through residential	Potential for on-site wells to result in ingestion	First potable well (low)	Five year reviews	Buy out water rights	1 month

Each uncertainty is entered on its own line of the matrix (e.g., Figure 8-1). The assumed value of a parameter or condition affecting the uncertainty (selection basis) is assigned to the uncertainty. The range of possible values that may be observed during implementation is estimated. The key is to try and bound the range with whatever information is available. In the end, if there is no basis for bounding the range, the entire span of possible values is entered.

A threshold value (e.g., decision criterion) is entered as the condition at which a deviation from the assumed value becomes significant (i.e., the point at which a different selection would have been made had the threshold value been the assumed value for the selection basis). Some uncertainties may have multiple thresholds, e.g., if the assumption is that there is no free floating pure phase product, the first threshold may be presence of a sheen which would warrant some pretreatment to protect the GAC, while the second threshold might be a layer in excess of 5 cm at which point free phase extraction would be employed. Thresholds should be associated with a qualitative estimate of the likelihood that actual conditions lie on the other side of the threshold than what has been assumed.

The impact of exceeding the threshold should be identified in the uncertainty matrix (e.g., Figure 8-1) and may prove useful in helping identify promising candidates for the contingency plan. The probability of exceeding the threshold is estimated qualitatively as a means of judging the likelihood that a contingency will have to be implemented and, therefore, the degree to which the contingency should be pre-mobilized.

A means of monitoring for deviations is identified as the way in which the uncertain parameter or condition will be observed to trigger implementation of the contingency. Clearly, the monitoring approach must be sensitive enough to be able to indicate when the threshold has been crossed. Ideally, monitoring provides a means of projecting forward so that there is some advance warning of when a threshold is likely to be exceeded, e.g., the use of dig face contamination data to extrapolate to volume remaining to be excavated.

In addition to the method, it is important to define what constitutes variability versus a deviation of concern. If there is no monitoring method available (i.e., uncertainty will not be resolved during implementation) then the design basis should be changed or a tolerant technology selected (e.g., if there is no follow-up on seeing if institutional controls are working, then they might not be a viable remedial option).

The contingency should indicate what action would be taken when a deviation has been substantiated by the monitoring activity. Finally, some measure of timing is important both with respect to the amount of advance warning afforded by the monitoring and with respect to the amount of response time required to implement the contingency. A comparison of the two time estimates will help with selection of the preferred contingency as well as a determination of the degree of predevelopment of the contingency that is warranted.

The matrix is developed by evaluating each uncertainty separately. Ultimately, it is important to review the content in a broader systems context. If too complex or too many contingencies are required, it may be that an alternate response is needed. There is also an opportunity to identify contingencies that address more than one uncertainty.

Uncertainty matrices in either form are valuable tools for communication with stakeholders. Uncertainty is a primary cause of concern with the public that often leads to requests for more extensive investigations and use of clean closure responses. By demonstrating that uncertainties have been systematically evaluated and monitoring and contingency plans are in place, the public is more likely to accept decisions made with less than complete knowledge. Indeed, the use of monitoring and irrevocable contingency actions has played a major role in gaining acceptance for monitored natural attenuation remedies.

Interpreting the Decision Document

The decision document provides the road map for all post-remedy selection activities. However, the utility of that road map is tied directly to the ability of the PMT to reach a consensus interpretation. In the best of circumstances, the PMT will have followed the Principles and had a heavy hand in preparing the decision document. That being the case, and assuming no changes in personnel on the PMT, a consensus interpretation will already exist. That not being the case, a consensus should be reached as soon as possible. The decision document by design will include requirements such as the identity of the response, its components, criteria and standards to be met, and other requirements. It will also include areas of flexibility and allowance within which there is latitude to meet RAOs using different creative approaches. It is these areas where streamlining and innovation can result in cost and resource savings.

While the decision document prescribes the required response, the level of detail provided will vary greatly. The decision document will also prescribe the constraints on the response (i.e., actions that can not be taken or options that can not be considered). The level of detail contained in the decision document reflects a balance between protection against misinterpretation and less opportunity for flexibility and innovation. Inherently, there is more flexibility when performance standards are specified in place of design standards. This is not meant to suggest that the level of detail or the provisions contained in the decision document are good or bad; rather, that the PMT needs to understand them before they know how to address them.

Standards and criteria should be clearly listed in the decision document. Most will be identified as ARARs or permit conditions. If they are not, the PMT will need to agree on which standards should be attained, and the extent to which they apply (i.e., to which media and at which locations). Decision documents should also include a section containing additional requirements that must be met. These requirements are not necessarily linked directly to solving the original problem; rather, they describe other legal frameworks under which the work must be conducted.

For all design bases, when dealing with environmental response actions, the PMT needs to assume there will be some surprises--no site is completely characterized (i.e., a range of values is always possible). The question then changes from "what if" to "what are the impacts if" the values exceed the estimate.

Essentially, the engineer looks at how the response would be designed if the extremes of the possible range were selected as the design basis. If the design is not significantly different, there may be no need for a contingency. If the design would be altered greatly, then it is prudent to evaluate the tradeoff between cost of a more robust design versus the cost of having a contingency in place to accommodate conditions that deviate from the design basis.

Contingency Development

In selecting a contingency, there are three relevant lines of inquiry:

- What is the impact of the potential deviation (uncertainty) and does it suggest an obvious contingency? (e.g., if the concern were unmapped preferential pathways being missed by a pump and treat system, the contingency would be to treat the receptor well or install new extraction wells when monitoring data reveal leakage.)

- What response would have been selected if the worst case value were assumed for the uncertainty? (e.g., look at the remedy that would have been selected if the deviation were assumed as the baseline condition.)

- Are there obvious options for moving from the selected response to the level of protection required if the worst case prevails? Can adding to the current design accommodate the deviation? (e.g., a second facility to take additional excavated soil if it exceeds capacity of the current facility.)

By pursuing these lines, it is possible to identify candidate approaches for the contingency.

Ultimately, any contingency that is implemented must be developed as fully as the response itself. However, a number of factors need to be considered in deciding how far the development should be taken prior to an indication that the triggering deviation will be encountered.

Clearly, primary importance needs to be placed on evaluating the impact of delays in implementation. The longer it takes to implement a contingency and the greater the impact of delays, the more incentives there are for pre-mobilization. For example, if the response involves open excavation and the contingency would leave the hole open and subject to subsequent releases of contamination during storm events, there is good reason to reduce the response time and minimize that potential or modify the contingency to include immediate cover for the excavation while the rest of the contingency is being mobilized.

In the example of excavation of soil that may contain hexavalent chromium, the health and safety implications are of sufficient importance that protective clothing should be selected on the assumption hexavalent chromium is present (i.e., fully pre-mobilized contingency). With regard to an alternate treatment approach if hexavalent chromium is encountered, the alternate method should be identified and logistics planned, but exhumed soil would not be treated for hexavalent chromium until its presence is confirmed.

The probability of deviations exceeding a threshold is an important consideration. If the probability is very low, there is less likelihood that the contingency will be implemented and, therefore, less incentive to fully develop it. Similarly, if the monitoring will provide warning of the likelihood of a deviation exceeding the threshold well in advance, there will be more time to develop the details of the contingency when it is clear that it is needed. In some respects, a good monitoring program with predictive capability can be viewed as a means of continually updating the probability estimate.

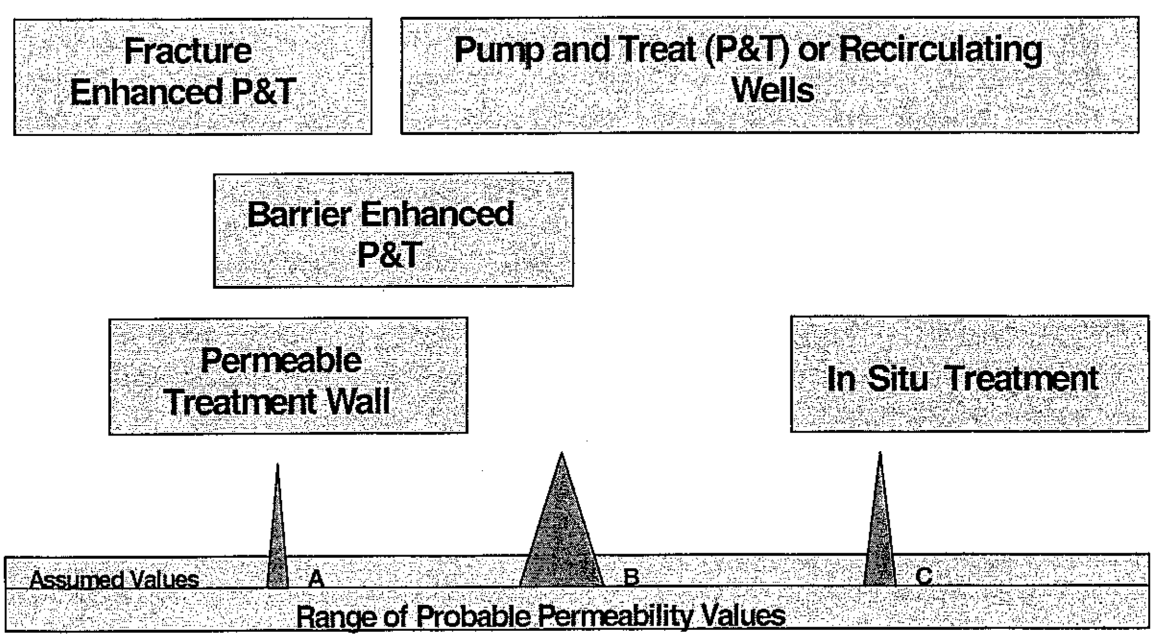
To the extent that a contingency is compatible with a response, it is easier to pre-mobilize than a contingency that will alter the remedy fundamentally. In the latter case, the point at which the trigger is encountered will impact the degree to which there is merit in stopping work and developing detailed plans for the change in direction. Obviously, the greater the resources required by a contingency, the greater the incentive to delay development until need is apparent.

At this point, it is clear that uncertainty mitigation consists of two key elements: 1) a monitoring plan (i.e., a means of determining if a deviation exists), and 2) a contingency plan (i.e., actions that will be taken if it is evident performance will not meet RAOs). Both elements are needed. Hence, any remedy that has a monitoring requirement should also have a contingency plan to be implemented if monitoring results indicate RAOs are not being met. (Monitoring implies there is residual uncertainty about performance. If that is not the case, there is no justification for monitoring in the first place.)

Tolerant technologies are defined as those that can accommodate the broadest range of conditions. Ideally, a technology is available that addresses the full range of probable values for the uncertain parameter. In that case, no contingency is required. In many respects the contingency has been completely pre-mobilized in the remedy design.

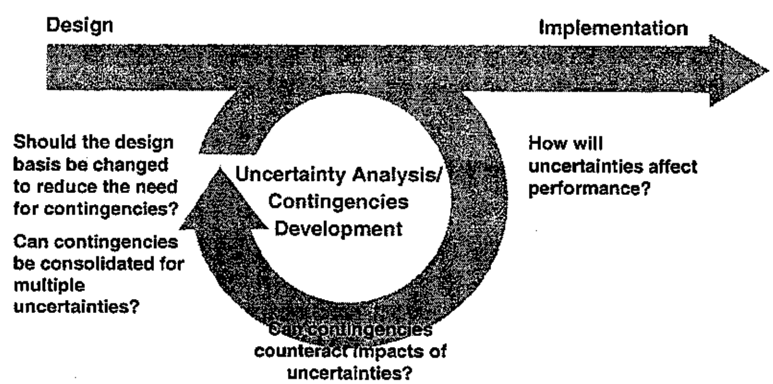
In Figure 8-3, the location of the assumed value (A, B, or C) would alter the selection of the response. The nature of any deviation from the assumed value would also identify candidate contingencies. If the assumed value is A, pump and treat or in-situ treatment cannot be applied. Permeable treatment walls, barrier enhanced pump and treat or fracture enhanced pump and treat would be candidates. If it is likely the assumed value is biased low, the treatment wall is the more robust option. If A is biased high, fracture enhanced pump and treat is the most robust option. If B or C is the assumed value for permeability, pump and treat/ recirculating wells are the most robust option.

Figure 8-3: Identifying Tolerant Technologies



When uncertainties in response selection and design have been addressed, there is an opportunity to step back again and review the plan in a systems context (Figure 8-4). If many and varied contingency plans are needed, there may be merit in looking for more robust contingencies that cover a larger number of uncertainties or to reconsider more tolerant technologies. Robustness may come from the technology itself or from the design.

Figure 8-4: Iterative Nature of Uncertainty Analysis



Uncertainty evaluation and management provide a mechanism to keep the response on track and moving through implementation toward completion. If a different design basis would alleviate the need for contingencies in the design, that basis could be the best probable value for design. Therefore, the uncertainty consideration is not viewed as a sequential process step, but an integral part of design that is reevaluated whenever new information comes to light. It is important to keep procurement staff in the loop as situations that require implementation of contingencies occur.

Ultimately, uncertainty analysis is a feedback mechanism in the design process that affects three areas:

- Final design;
- Procurement; and
- Nature of contingencies.

Summary

Mitigation is required for all residual uncertainties of significance (i.e., those that may cause the response to fail to meet RAOs). Mitigation may be accomplished by selecting technologies or designs that are tolerant of the full range of possible values for an uncertain parameter or by monitoring uncertain parameters during implementation and implementing pre-determined contingencies as appropriate. The best approach to mitigation is determined on the basis of the nature of the uncertainty and the potential impacts of probable deviations from assumed conditions.

Variations of the uncertainty matrix are useful in evaluating alternatives for mitigation in both the pre-decision and post-decision document timeframes. Matrices in any form can be an effective means of communicating with stakeholders and gaining greater confidence in the level of protectiveness that will be provided by a selected response.

The degree to which contingencies are pre-mobilized should be determined on the basis of impacts, resource requirements, and timing. In the extreme, tolerant technologies are selected such that the contingency is fully implemented without knowledge of whether it is needed.